Land use relationships for a rare freshwater mussel species (Family: Unionidae) endemic to central Texas

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Charles Randklev
Texas A&M University

Hsiao-Hsuan (Rose) Wang
Texas A&M University

Julie E Groce
Vegetation Link

Articles

Land Use Relationships for a Rare Freshwater Mussel Species Endemic to Central Texas

Charles R. Randklev,* Hsiao-Hsuan Wang, Julie E. Groce, William E. Grant, Stirling Robertson, Neal Wilkins

C.R. Randklev
Institute of Renewable Natural Resources, Texas A&M University, College Station, Texas 77843

H.-H. Wang, W.E. Grant
Department of Wildlife and Fisheries Sciences, Texas A&M University, College Station, Texas 77843

J.E. Groce
School of Biological Sciences, Monash University, Clayton, Victoria, Australia 3800

S. Robertson
Texas Department of Transportation, Environmental Affairs Division, Austin, Texas 78704

R.N. Wilkins
East Wildlife Foundation, San Antonio, Texas 78216

Abstract

We assessed the influence of geology, land use, and other features on the occurrence of the rare freshwater mussel smooth pimpleback, *Quadrula houstonensis,* in the Leon River, Texas. Boosted regression trees were used to assess the relationships between the species' occurrence and potential explanatory variables based on field data from 52 sampling locations. The individual variables that best explained prevalence for this species were downstream distance from reservoirs, percentage of shrubland within the riparian buffer, and percentage of alluvium and aquifer bearing rock-types. These results indicate that smooth pimpleback may be sensitive to flow modification and changes in land use that increase sedimentation. The application of similar modeling efforts to other rare species in this region could help in their management and conservation.

Keywords: boosted regression trees; candidate species; southwest; species distribution model; Unionid

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* Corresponding author: crandklev@ag.tamu.edu

Introduction

Freshwater mussels (Bivalvia: Unionidae) play an important role in freshwater ecosystems through nutrient cycling; increasing habitat heterogeneity; and as a food source for some fishes, mammals, and birds (Haag and Williams 2013). North America contains the highest diversity of unionid mussels, with about 300 recognized species (Williams et al. 1993). However, many of these species are in decline or have become extinct because of habitat loss or elimination of host fish (Neck 1982; Williams et al. 1993; Lydeard et al. 2004; Haag and

Williams 2013). In Texas, similar declines have occurred but until recently have gone largely unnoticed. Currently, there are 15 species listed as state threatened (TPWD 2010), of which 6 are candidates (USFWS 2001, 2011) for protection under the U.S. Endangered Species Act (ESA 1973, as amended). As a result, mussel conservation strategies are now beginning to emerge in Texas. One strategy includes the development and use of species distribution models (SDMs) to model the occurrence of state-threatened mussel species. Such tools will improve conservation activities by allowing resource managers to 1) estimate habitat suitability and assess range curtailment; 2) forecast the effects of habitat change due to altered land-use patterns, modifications of free-flowing rivers, or climate change; 3) predict "hotspots" of mussel species persistence; and 4) identify potential locations for species introductions.

The distribution and occurrence of aquatic biota are mediated by environmental variables operating at varying temporal and spatial scales, such that at the local scale, habitats develop within the constraints set by watershed features (Frissel et al. 1986; Poff 1997). For example, surface geology influences channel morphology and hydrological patterns. These factors, in turn, structure local habitat by mediating bed scouring and the frequency of floods (Strayer 1983; Gangloff and Feminella 2007). Also important, are anthropogenic changes to the landscape, such as the conversion of native land cover to agriculture crop production, which can degrade local habitat through increased inputs of sediments, nutrients, and environmental contaminants (Brim Box and Mossa 1999; Poole and Downing 2004; Lyons et al. 2007). Among unionid mussels, watershed characteristics such as stream size, surface geology, hydrological variability, and land use are known to affect the broad-scale distributions of mussels (Strayer 1983; Di Maio and Corkum 1995; Arbuckle and Downing 2002). At local spatial scales, such as a reach (10^1–10^3 m in length; Frissel et al. 1986; Allan 2004), substrate stability during high flows, habitat quality, geology, and composition of riparian vegetation have been shown to be influential (Howard and Cuffey 2003; McRae et al. 2004; Poole and Downing 2004; Gangloff and Feminella 2007).

Although it is clear that mussel distribution is influenced by watershed- and reach-scale characteristics, there is increasing evidence that the degree to which those characteristics influence mussel assemblages can vary. For example, Poole and Downing (2004) examined the relationship between local extinction rates and environmental factors in an agricultural landscape in Iowa and found that declines in mussel species richness were tied to increases in agricultural land use and decreases in the prevalence of geological formations and alluvial deposits that influenced water recharge at the watershed scale. Habitat at the local scale reflected these land-use changes; sites within agriculture-dominated watersheds exhibited deforested riparian zones with low substrate heterogeneity and, as a consequence, lower mussel species richness. In contrast, McRae et al. (2004) found that in the River Raisin in southeastern Michigan, local-scale factors such as flow stability, overall habitat quality, percentage of fine particles, and local geology were better predictors of total mussel abundance than watershed characteristics. Watershed-scale variables, such as surface geology, were also found to be important, but their effect on mussel distribution appeared to be more subtle compared with reach-scale factors.

These studies demonstrate that mechanisms mediating mussel distributions operate at multiple spatial scales and that each scale varies in its influence. Because of this, effective conservation efforts for freshwater mussels will require an understanding of how watershed characteristics influence mussel persistence and the importance of these factors relative to local scales. Unfortunately, knowledge regarding the factors and scales that influence mussel assemblages is still in an early stage of development (Newton et al. 2008), particularly in Texas, where much of the research on mussel–habitat relationships has been primarily descriptive and focused at the local scale. In this study, we analyzed the relationship between the occurrence of the freshwater mussel smooth pimpleback, *Quadrula houstonensis* (I. Lea 1859), in the Leon River, Texas, and several environmental variables representing the surrounding landscape at different spatial scales. Our goal was to explore whether predictive models could be developed for this species in a basin where an improved understanding of its distribution could aid in its conservation.

Methods

Study area

The study was conducted in the Leon River (a tributary of Little River) in the Brazos River basin. The Leon River is located in the North Central Prairie and Cross Timbers regions of central Texas (Figure 1) and exhibits a subhumid climate with hot summers and dry winters (Harmel et al. 2008). The dominant land uses are rangeland (63%) and agriculture (10%), and both have likely degraded water quality through nutrient inputs from dairies, manure application sites, cattle encroachment, and pesticide and fertilizer runoff (Rossi et al. 2008). Currently, portions of the Leon River and associated tributaries are considered impaired as a result of elevated bacterial levels and low dissolved oxygen (TCEQ 2012).

Three major reservoirs, completed in the 1950s and 1960s, are located on the main stem of the Leon River to help control flooding and water supply for commercial and residential purposes. Belton Lake, located in Bell County, is operated by the U.S. Army Corps of Engineers and is the largest reservoir, with a capacity of 5.36×10^8 m^3 and covering 49 km^2 at conservation pool. Floodwater is released from Belton Lake through three controlled intake structures, located at the middle and bottom of the dam, while conservation releases occur via outlet works near the middle of the dam. (Dowell and Breeding 1967; Harmel et al. 2008). Lake Leon is located on the upper segments of the Leon River in Eastland County and is owned and operated by the Eastland County Water Supply District (Dowell and Breeding 1967). The

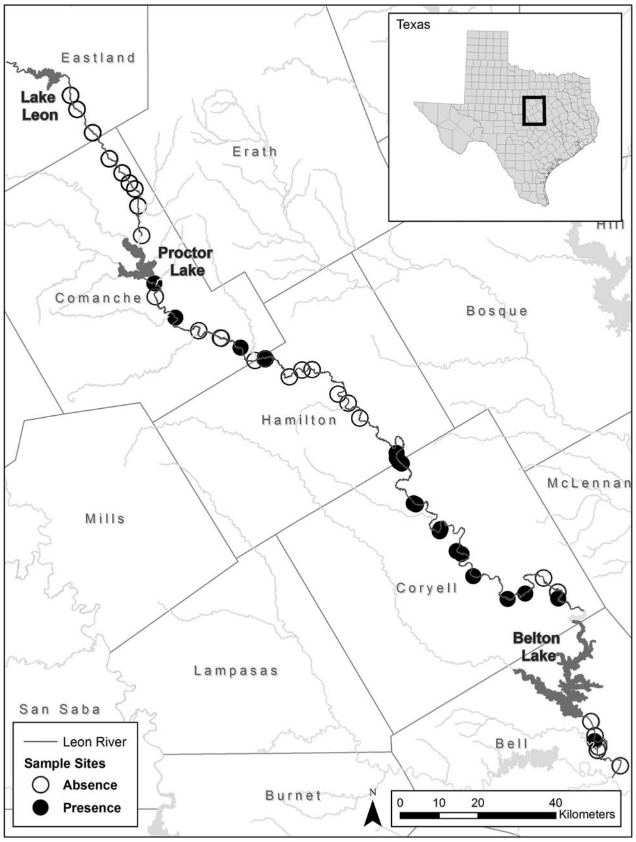

Figure 1. Survey sites for smooth pimpleback, *Quadrula houstonensis,* in the Leon River, Texas, between May and August 2011. Shaded circles denote locations where live smooth pimpleback was detected, unshaded circles denote locations where smooth pimpleback was not detected.

reservoir has a capacity of 3.37×10^7 m^3 and covers 6 km^2. Release of water for conservation use is uncontrolled and occurs through the service spillway located near the center of dam (Dowell and Breeding 1967). Proctor Lake, in Comanche County is operated by the U.S. Army Corps of Engineers and has a capacity of 6.84×10^7 m^3 and covers 18 km^2. During conservation releases, water is discharged through two gated outlets near the bottom of the dam (Dowell and Breeding 1967).

Mussel data

Smooth pimpleback is a candidate species under the Endangered Species Act (ESA 1973; USFWS 2011). This species occurs in the central and lower reaches of the Brazos and Colorado rivers and their tributaries in central Texas (Howells 2010). Within the Leon River, smooth pimpleback appears to have a restricted distribution and is found primarily in the middle reaches of the river upstream of Belton Lake (Randklev et al. 2013).

Occurrence data for this species were collected during a survey performed by Randklev et al. (2013) between May and August 2011. The main intent of their survey was to examine river-wide patterns of mussel diversity in the mainstem of the Leon River. Site selection was informal and based on presence of potential mussel habitat (e.g., riffle, runs, woody debris, backwater, undercut banks) and whether the site was in an area that could be reached from a point of public access. Their survey methodology followed that of Metcalfe-Smith et al. (2000), and was designed to provide guidance on the amount of effort needed to locate rare species by collecting as many individuals as possible during one or more search periods. Specifically, surveyors searched for mussels using visual and tactile (i.e., handpicking) techniques for a minimum of 1 person-hour (where 1 p-h = 60 min/number of surveyors). Additional 1 p-h searches were added until no new species were recorded.

Fifty-two sites were surveyed and smooth pimpleback was observed at 24 of these locations. Sites ranged from 150 to 2,132 m^2 (median = 818 m^2), but >75% were between 210 and 1,100 m^2 and all were wadeable. Search effort, calculated as the total amount of time spent surveying a site multiplied by the number of surveyors, ranged from 1 to 26 person-hours (median = 2.5 person-hours [p-h]), but >90% were between 1 and 5 p-h. There were only three locations where search time exceeded 5 p-h and, at those locations, the increase in search effort was due to a larger survey crew (i.e., 6-person survey team compared with the 4-person survey team used at most other sites). The size of the search area was not standardized between sampling locations, it is plausible that variability in search area influenced survey-discovery probability for smooth pimpleback. To test whether this is the case, we examined the relationships among search area, search effort, total number of species, and total number of live mussels. All correlations were nonsignificant, indicating that no discovery probability bias was introduced related to unstandardized search areas: search effort (p-h) versus search area, $R = -0.07$, $P = 0.65$; log total number of species versus search area, $R = -0.20$, $P = 0.19$; and log total number of live mussels versus search area, $R = -0.22$, $P = 0.15$).

Land-use models

Previous studies suggest the following factors may be appropriate explanatory variables for predicting mussel occurrence: landscape features such as percentages of different land cover types (Hopkins 2009; Burlakova et al. 2011); site conditions such as the percentages of different flooding classes (Hastie et al. 2001a; Negishi et al. 2012); geology (Strayer 1983; Arbuckle and Downing 2002; Meador et al. 2011); levels of erosion (Black et al. 2010; Allen and Vaughn 2011); and factors such as the distances upstream and downstream to the nearest dam (Vaughn and Taylor 1999; Watters 1999) and the length of roads within the adjacent area on either side of the reach (Cosgrove and Hastie 2001; Cooksley et al. 2012). We tested these variables against the occurrence of smooth pimpleback using geo-referenced data. Data sources included the Environmental Systems Research Institute, the National Agricultural Statistics Service, the National Inventory of Dams, the Natural Resources Conservation Service, the U.S. Geological Survey, and the Bureau of Economic Geology at the University of Texas at Austin (Table 1).

Table 1. Description and data sources of land use and land cover composition, geology composition, fluvial processes, and anthropogenic factors evaluated as potential determinants of the distribution of smooth pimpleback, *Quadrula houstonensis,* in Leon River, Texas. Presence and absence data for smooth pimpleback in the Leon River are from qualitative surveys conducted between May and August 2011. Abbreviations listed in the table denote the following: ESRI = Environmental Systems Research Institute; NASS = National Agricultural Statistics Service; NID = National Inventory of Dams; NRCS = Natural Resources Conservation Service; USGS = U.S. Geological Survey; UT_BEG = University of Texas at Austin Bureau of Economic Geology.

Variable class	Variable description	Data source
Land use and land cover	Percent agriculture land	NASS
	Percent developed land	NASS
	Percent forest land	NASS
	Percent grassland	NASS
	Percent shrubland	NASS
	Percent wetland and water body	NASS
Geology composition	Percent fluviatile	UT_BEG
	Percent Cretaceous—aquifer	UT_BEG
	Percent Cretaceous—nonaquifer	UT_BEG
	Percent alluvium	UT_BEG
Fluvial processes	Slope of the reach	USGS
	Percent "none" flooding class	NRCS
	Percent "occasional" flooding class	NRCS
	Percent "frequent" flooding class	NRCS
	Percent negligible erosion	NRCS
	Percent slight erosion	NRCS
	Percent moderately severe erosion	NRCS
Anthropogenic factors	Distance (km) upstream to nearest dam	NID
	Distance (km) downstream to nearest dam	NID
	Length (km) of roads within buffered reach	ESRI

Data analysis

Based on recommendations of Allan (2004), we analyzed relationships between the occurrence of smooth pimpleback and potential explanatory variables both at the reach and riparian scale. We analyzed two reach scales, consisting of a 500- buffer extending upstream from the sample location with 1) a 100-m buffer, and 2) a 200-m buffer perpendicular to the stream center; and two riparian scales, consisting of a 1,000-m buffer extending upstream from the sample location with 1) a 100-m buffer, and 2) a 200-m buffer perpendicular to the stream center. Catchment-scale patterns, while important, were not addressed because the fine-scale variation for many of our predictor variables at this scale (e.g., land cover) were reduced compared with the reach and riparian scales. As result, we felt that catchment-scale models could be potentially misleading, especially for predictor variables where the number of land cover elements are so few that idiosyncrasies in their arrangement would drive the results of the model.

We conducted our analysis at each of these 4 spatial scales using boosted regression trees (BRTs), which combine decision trees and a boosting algorithm with a form of logistic regression (Hastie et al. 2001b; Elith et al. 2008; Hopkins 2009). For BRTs, the probability of species occurrence at a location is modeled as a function of the set of potential explanatory variables using a logit link (e.g., Elith et al. 2008). We fitted all BRTs using R (R Development Core Team 2006 version 2.14.1) with the gbm package version 1.5-7 (Ridgeway 2006), plus the custom code that is available online (Elith et al. 2008).

Our aim here was to find the best combination of parameters (learning rate and tree complexity) that achieved minimum predictive deviance. The learning rate, also known as the shrinkage parameter, determines the contribution of each tree to the growing model, and the tree complexity controls whether interactions are fitted. We determined the optimal model at each spatial scale following the recommendations of Elith et al. (2008) by altering the learning rate and tree complexity (the number of split nodes in a tree) until the predictive deviance was minimized without overfitting, and by limiting our choice of the final model to those that contained at least 1,000 trees. We included randomness in our models to improve their accuracy and to reduce overfitting (Friedman 2002). We represented randomness using a "bag fraction" that specifies the proportion of the data to be selected at each step (Elith et al. 2008). We set the bag fraction at 0.8, meaning that 80% of the data were drawn at random without replacement from the full training set at each iteration.

Model predictive error was assessed using a ten-fold cross-validation with resubstitution (e.g., Elith et al. 2008). For each cross-validation trial, we randomly selected 80% of the data set for model fitting and we used the excluded 20% for testing. We then used the resulting data to calculate the response variance explained, the area under the receiver operator characteristic curve, overall accuracy, and omission (areas of presence predicted absent) and commission (areas of absence predicted present) error rates (Hosmer and Lemeshow 2000).

To determine the relative importance of predictor variables, we used the gbm package (Ridgeway 2006). The measures in this package are used to determine the contribution of each variable by tabulating the number

Table 2. Characteristics of the best-fitting boosted regression trees model predicting the distribution of smooth pimpleback, *Quadrula houstonensis,* in the Leon River, Texas. Presence and absence data for smooth pimpleback in the Leon River are from qualitative surveys conducted between May and August 2011. Potential explanatory variables were analyzed at the reach scale (500-m upstream buffer) with a 100-m buffer perpendicular to the stream center. AUC—area under the receiver operator characteristic curve.

Model characteristic	Value
No. of trees	1,100
Predictive deviance	1.007 ± 0.105
Total response variance explained	84.7%
AUC	0.842 ± 0.069
Overall accuracy	88.6%
Commission error rate	9.1%
Omission error rate	2.3%

of times a variable is selected for splitting, weighted by the squared improvement to the model as a result of the split, and averaged over all trees. The resulting data are then scaled from 0 to 100, such that higher numbers indicate stronger influence (Elith et al. 2008). We then used the gbm package to constructed partial dependence plots for the most influential variables.

To visualize the output from the BRTs analysis, we first delineated the entire length of the Leon River into 500-m intervals (hereafter, mapping segments) using ArcMap 10 (Environmental Systems Research Institute, Redlands, CA). The habitat variables were then quantified for each mapping segment and used to determine each segment's predicted probability of occupancy using the fitted BRTs. Probability values per segment were mapped and color-coded using ArcMap 10.

Field validation

To test the accuracy of our SDMs, we generated random point samples for field validation within the same mapping segments used to visualize the output from the BRTs. Stream segments that contained the original sampling locations were removed from the validation data set. The remaining reaches were categorized into 5 probability classes (0–20%, 20–40%, 40–60%, 60–80%, and 80–100%). We employed the random point generator in ArcMap 10 to select sites within each of the probability classes for field validation. Sampling methods at the field validation sites followed those reported by Randklev et al. (2013) to ensure that presence and absence data were collected in a manner similar to those used to develop our models.

Results

All four best-fitting BRTs models possessed good ability to discriminate between species presence and absence (area under the receiver operator characteristic curve score >80%; Table S1, *Supplemental Material*). However, the best-fitting BRTs model with regard to predictive deviance, total response variance explained, overall

Table 3. Relative contributions (%) of the eight most influential environmental covariates to the best-fitting boosted regression trees models predicting the distribution of smooth pimpleback, *Quadrula houstonensis,* in the Leon River, Texas. Potential explanatory variables were analyzed at the reach scale (500-m upstream buffer) with a 100-m buffer perpendicular to the stream center. Presence and absence data for smooth pimpleback in the Leon River are from qualitative surveys conducted between May and August 2011.

Variable class	Variable description	Relative contribution (%)
Anthropogenic	Distance (km) upstream to nearest dam	46.52
Geology	Percent alluvium	32.26
Anthropogenic	Length (km) of roads within buffered reach	4.96
Land use and land cover	Percent shrubland	4.62
Geology	Percent Cretaceous-aquifer	4.45
Land use and land cover	Percent agriculture land	4.28
Land use and land cover	Percent grassland	1.66
Land use and land cover	Percent developed land	1.25

accuracy, commission error rate (false positive), and omission error rate (false negative) was the reach scale (500-m upstream buffer) with a 100-m buffer perpendicular to the stream center (Table 2). The top explanatory variables for this model were distance upstream to the nearest dam and percent alluvium (Table 3). Predictor variables related to anthropogenic factors (i.e., dams and roads; Table 1) were most influential in predicting mussel distribution (accounting for 51% of the predictive ability), followed by geological composition (37%), and land use and land cover (12%; Table 3).

Partial dependency plots (Figure 2) indicated that high-occupancy cells were located 140 km downstream from the nearest dam, and had <0.2 km length of roads within the buffered reach. Partial dependency plots of explanatory variables associated with geological composition indicated high-occupancy cells consisted of <65% of alluvial deposits and had >5% of Cretaceous aquifer bearing rock-types. Finally, partial dependency plots of explanatory variables associated with land use and land cover indicated high-occupancy cells had <6% of shrubland, 4% of agriculture land, and 5% of developed land, but had >30% of grassland within the reach buffer. Application of the best-fitting BRTs model along the Leon River indicates that stream segments in the middle reaches of the river (i.e., between Proctor Lake and Belton Lake) were ≥50% more likely to harbor smooth pimpleback compared with stream segments immediately downstream from reservoirs, irrespective of spatial scale (Figure 3; Table S2, *Supplemental Material*).

We surveyed 17 sites to field-validate the model predictions and detected smooth pimpleback at 9 sites.

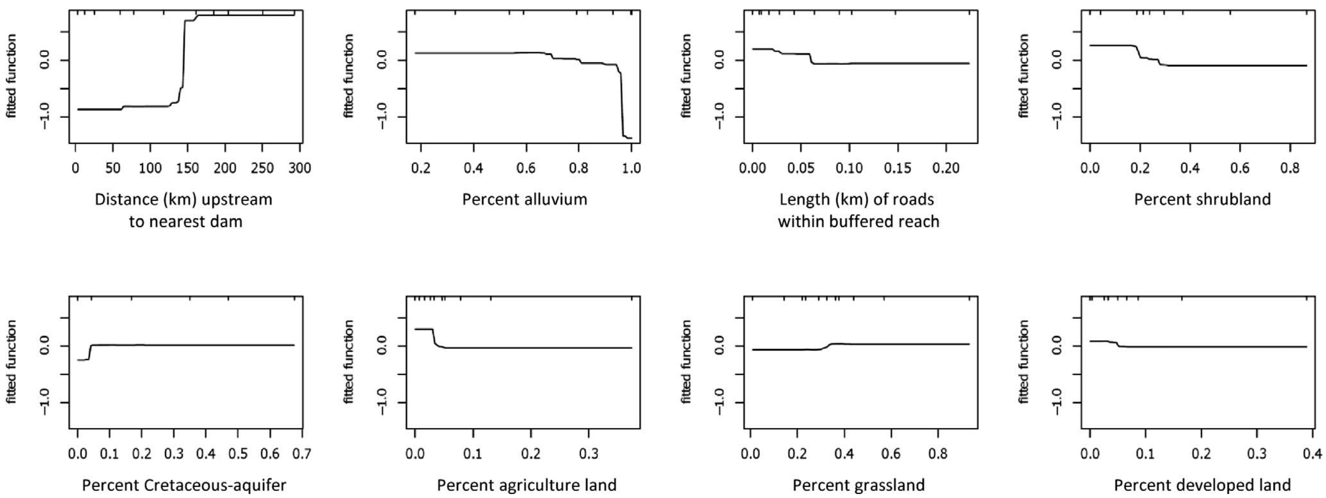

Figure 2. Partial dependence plots for the explanatory variables included in the best-fitting boosted regression trees model (reach scale [500-m upstream buffer] with a 100-m buffer perpendicular to stream center) for smooth pimpleback, *Quadrula houstonensis,* based on analyses of the eight most influential variables. Presence and absence data for smooth pimpleback in the Leon River, Texas, are from qualitative surveys conducted between May and August 2011. Plots are ordered from the highest to lowest importance of each variable. Hash marks at the top of each plot indicate the locations of sample sites along the range of the indicated variable. *Y*-axes are on the logit scale and show the effects of a variable on the response after accounting for the average effects of all other variables in the model (Elith et al. 2008).

Based on occupancy probability categories of <20%, 20–40%, 40–60%, 60–80%, and 80–100%, the reach scale (500-m upstream buffer) with the 100-m buffer perpendicular to stream center performed well in river segments where predicted occupancy was high (60–100%; Table 4). The model was less accurate in river segments where predicted occupancy ranged from 0% to 40% (Table S3, *Supplemental Material*).

Discussion

Model performance

We were able to develop distribution models for smooth pimpleback at the reach and riparian scales using BRTs. We found that the reach scale (500-m upstream buffer) with 100-m buffer perpendicular to stream center exhibited better overall accuracy and lower commission and omission error rates. The results from the field validation corroborate these statistical results; however, because the sample size for field validation varied per probability category, additional surveys would be needed to determine whether these differences are real or an artifact of small sample sizes.

Our findings have important implications for the conservation of smooth pimpleback and related land-use analyses. First, there have been few studies in Texas, or the southwestern United States, that have attempted to empirically assess mussel distribution relative to land use. This is not to say that our results are not without limitations (see below), but they do demonstrate that landscape features can be used to investigate factors mediating the distribution of rare unionid mussels. Thus, our findings could be used as a framework for developing SDMs for other threatened mussel species in the Southwest. Second, our analyses confirm those by Hopkins (2009) that BRTs is a useful technique for modeling mussel species distributions, even with small data sets such as those presented in this study. Lastly, most mussel land-use analyses lack independent data sets with which to test their conclusions about mussel distribution or habitat use (Newton et al. 2008). Ground-truthing efforts such as those included here are important for validating model output and assessing their appropriateness for use in making management decisions.

Although our modeling effort was successful, there were some shortcomings in our approach. First, we did not take into account the influence of past land-use activity, which has been shown to be equally, if not more, important than contemporaneous changes to the landscape regarding declines in biodiversity (Harding et al. 1998). Second, because we did not characterize physical habitat at each sample site, it is reasonable to assume that predictive probabilities generated from our models may not be entirely accurate due to variability in microhabitat conditions; this may explain some of the discrepancies observed in our field validation efforts. Third, although our models are predictive for the Leon River, it is unknown whether they can be applied to other streams and rivers outside of this basin where smooth pimpleback is known to occur. Finally, our models do not distinguish between locations where populations for this species are recruiting and expanding versus those where recruitment is not occurring and the populations are declining.

Species–environment relationships

The individual variables that best explained the prevalence of smooth pimpleback were distance to the nearest impoundment and decreasing proportion of shrubland and alluvium. It is well-known that dams fundamentally transform river ecosystems by altering

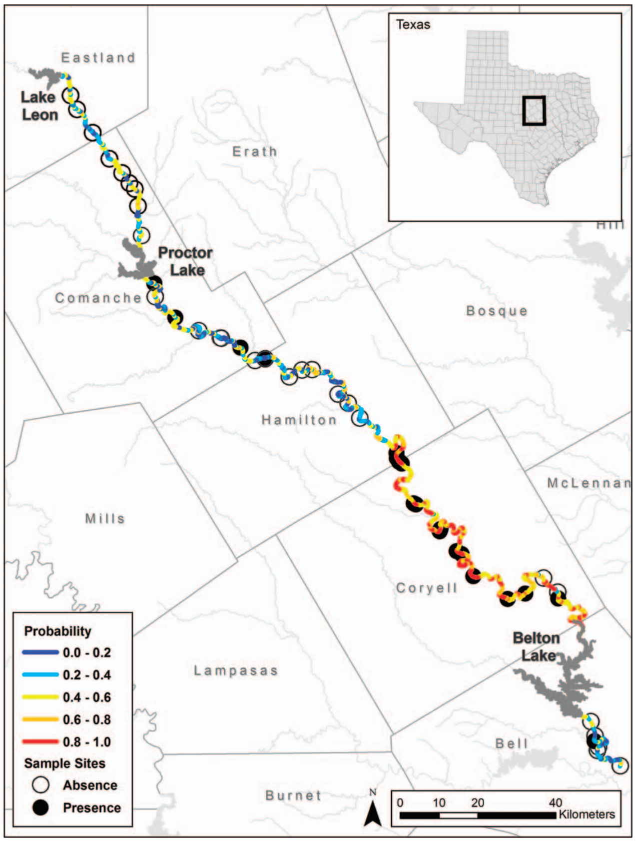

Figure 3. Predicted distribution map for smooth pimpleback, *Quadrula houstonensis,* based on the best-fitting boosted regression trees models for the reach scale (500-m upstream buffer) with 100-m buffer perpendicular to stream center. Survey sites for smooth pimpleback in the Leon River, Texas, are from qualitative surveys conducted between May and August 2011. Shaded circles denote locations where live smooth pimpleback was detected, unshaded circles denote locations where smooth pimpleback was not detected.

hydrological regimes, eliminating and fragmenting habitats, and disrupting patterns of energy flow (Poff et al. 1997; Rosenberg et al. 2000; Pringle 2003; Graf 2006). These changes may affect mussel survivorship, growth, and reproduction, which can lead to reductions in abundance and extirpation of rare species (Heinricher and Layzer 1999; Vaughn and Taylor 1999; Galbraith and Vaughn 2010). In this study, smooth pimpleback was found to be largely associated with stream segments located at considerable distances (>150 km) downstream from impoundments, indicating that this species is sensitive to flow modification or one of the many other physiochemical habitat parameters that change as a result of dams. Impoundments on the Leon River were constructed for flood control and residential and commercial purposes; therefore, it is likely that the pathways by which they influence mussel populations are different from those reported downstream of hydroelectric dams (Vaughn and Taylor 1999).

The absence of smooth pimpleback in stream segments located <150 km downstream of dams on Leon River may be explained, in part, by scouring and sedimentation associated with impoundment releases, with the former occurring immediately downstream of dams and the latter taking place further downstream. Generally, water released from reservoirs results in downcutting and coarsening of the riverbed (Gore et al. 1990; Kondolf 1997). For mussels, these erosional processes can impair mussel reproduction and contribute to instances of high mortality (Miller et al. 1992; Layzer et al. 1993). The sediment that is entrained during such processes can be problematic because it is typically deposited, often suddenly, at some distance downstream from the dam. However, for reservoirs that reduce flood peaks, such as those on the Leon River, the entrained sediment is usually not transported very far downstream (Ligon et al. 1995; Kodolf 1997). In our study, we found that stream reaches located <150 km downstream of dams generally had higher percentages of alluvium (83%), which is a measure of unconsolidated sediments, than reaches further downstream (65%); this may indicate higher rates of sedimentation in those reaches. Deposition and accumulation of fine sediment is detrimental to mussels because it can bury adults and juveniles, slow or inhibit growth by impeding respiration and degrading food quality, and cause reproductive failure either directly, by affecting gametogensis and fertilization, or indirectly, by eliminating habitat for host fish (Kat 1982; Aldridge et al. 1987; Houp 1993).

In addition to sedimentation and scouring, the presence of dams along the Leon River has likely contributed to declines in flow during periods of low rainfall and drought, which in turn has likely affected mussel populations for smooth pimpleback. Generally, stream flow in this region is maintained by a combination of conservation releases from nearby reservoirs and groundwater inputs. For the Leon River, it is likely that such releases are insufficient for stabilizing surface flows during periods of extreme low flow. Randklev et al. (2013) observed that during drought conditions, stream segments immediately downstream of Lake Leon and Proctor Lake were largely intermittent, while those further downstream continued to flow. Increased sediment loads near Belton and Proctor lakes may have also played a role by physically impeding surface–ground water exchange. In this study, we found that the percentage of alluvium and aquifer rock-bearing types were conversely related, such that with increased distance downstream from reservoirs the percentage of alluvium decreased while the percentage of aquifer rock-bearing types increased. Intermittency and loss of habitat, whether from inadequate reservoir releases or attenuated ground-water inputs, can impact mussels by exposing them to high water temperatures, loss of physical habitat, decreased food availability, higher rates of predation through stranding, low dissolved oxygen, and higher concentrations of organic and inorganic pollutants (Golladay et al. 2004). Although we did not quantify these particular impacts, it is likely that droughts compounded by attenuated reservoir releases and groundwater inputs have contributed to population declines for smooth pimpleback.

Table 4. Summary of field validation surveys for smooth pimpleback, *Quadrula houstonensis,* compared with probability of occurrence predicted by the best-fitting boosted regression trees model (reach scale [500-m upstream buffer] with a 100-m buffer perpendicular to the stream center) in the Leon River, Texas. Percentages and numbers in parentheses denote number of field sampling sites where smooth pimpleback was detected (% Present) or not detected (% Absent) per probability category. Field surveys for smooth pimpleback were conducted between May and August 2011.

Model	Predicted probability of occurrence (%)	No. of field sampling sites	% Present	% Absent
500 × 100 m	80–100	4	100% (4/4)	0% (0/4)
(Reach)	60–80	3	67% (2/3)	33% (1/3)
	40–60	3	33% (1/3)	67% (2/3)
	20–40	4	0% (0/4)	100% (4/4)
	<20	3	67% (2/3)	33% (1/3)

Cattle encroachment and subsequent changes to the riparian buffer may be another factor influencing the distribution of smooth pimpleback on the Leon River. Our analyses indicate that smooth pimpleback was largely absent from stream reaches where the percentage of shrubland within the riparian buffer exceeded 5%. For our study, shrubland encompassed land-cover elements primarily related to grazing; so it is conceivable that, for reaches where this shrubland is proportionately more abundant, cattle are accessing the river more frequently than those where the riparian buffer is largely intact. Livestock can affect mussels through trampling and nutrient inputs, and by degrading stream banks, which can lead to changes in hydrology and increases in local rates of sedimentation (Brim Box and Mossa 1999). We also found that the percentage of shrubland decreased with distance downstream from reservoirs, indicating that reservoirs along the Leon River may be negatively affecting native riparian communities. Generally, changes to the flow regime combined with declines in groundwater inputs can eliminate native riparian species, which may lead to riparian communities more characteristic of adjacent land uses (Nilsson and Jansson 1997; Nilsson and Berggren 2000), which for the Leon River is primarily rangeland. Changes to the riparian buffer are a concern because they can bring about increases in local sedimentation and exacerbate inputs of organic and inorganic pollutants. These impacts are detrimental to mussels because they affect growth, survivorship, and reproduction.

Management implications

Our study demonstrates the utility of SDMs, specifically BRTs, to model and map the distribution of a rare and imperiled unionid mussel and provide information that may aid in its conservation. Applying these models to river basins similar to the Leon River or to other rare mussel species could be useful for defining suitable habitat, discovering new populations, and planning transplantation or reintroduction experiments. Resource managers and conservationists could use our models to better manage local and riparian conditions for smooth pimpleback in the Leon River. Management at these scales should consider the impact of reservoir releases on riparian zones and mussel habitat and whether they are adequate to maintain existing populations of this species during periods of low flow, as well as the degree to which livestock and grazing practices are fragmenting the riparian buffer.

To realistically implement the strategies listed above, resource managers will need the flexibility to target and prioritize stream segments for conservation. To do this, stream segments in Leon River could either be ranked based on a species range, status, or endemism, or classified based on similarities or dissimilarities in abiotic attributes between sample locations (Moilanen et al. 2008; Hopkins and Whiles 2011). For example, Hopkins and Whiles (2011) developed SDMs for mussels and fishes in the Green River, Kentucky, using environmental data captured at several spatial scales. The models were then used to delineate conservation areas at the different scales using a rank-based approach. Although there are limitations to ranking stream segments based on output from SDMs, the method outlined by Hopkins and Whiles (2011) could serve as an example of how to select reaches in the Leon River for landscape management.

Supplemental Material

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Table S1. Summary of best-fitting boosted regression trees models predicting the distribution of smooth pimpleback, *Quadrula houstonensis,* in the Leon River, Texas. Potential explanatory variables were analyzed at the reach (500-m upstream buffer with a 200-m perpendicular buffer) and riparian (1,000-m upstream buffer and 100- or 200-m perpendicular buffers) scales. Presence and absence data for smooth pimpleback in the Leon River are from qualitative surveys conducted between May and August 2011.

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Table S2. Predicted probability of occupancy for smooth pimpleback, *Quadrula houstonensis,* at the reach scale in a 500-m reach extending upstream from the sample location with a 100-m buffer perpendicular to the stream center. Presence and absence data for smooth pimpleback in the Leon River, Texas, are from qualitative surveys conducted between May and August 2011.

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Table S3. Summary of field validation surveys for smooth pimpleback, *Quadrula houstonensis,* relative to predicted probability of occupancy at the reach scale (500-m upstream buffer with a 100-m buffer perpendicular to the stream center). Field validation surveys for smooth pimpleback in the Leon River, Texas, were conducted between May and August 2011.

Found at DOI: http://dx.doi.org/10.3996/012015-JFWM-003.S1 (58 KB XLSX).

Reference S1. Dowell CL, Breeding SD. 1967. Dams and reservoirs in Texas: historical and descriptive information. Report number 148. Austin, Texas: Texas Water Development Board.

Found at DOI: http://dx.doi.org/10.3996/012015-JFWM-003.S2 (59 MB PDF).

Reference S2. Gore JA, Nestler JM, Layzer JB. 1990. Habitat factors in tailwaters with emphasis on peaking hydropower. Technical Report EL-90-2, prepared for Department of the Army, U.S. Army Corps of Engineers, Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Found at DOI: http://dx.doi.org/10.3996/012015-JFWM-003.S3; also available at http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA218670 (4018 KB PDF).

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